Development of a Calibrated Watershed Model, Potomac River Basin

A Cooperative Project between the U.S. Geological Survey (USGS), the Interstate Commission on the Potomac River Basin (ICPRB), the Maryland Department of the Environment (MDE), and the U.S. Environmental Protection Agency Chesapeake Bay Program Office (CBP)

Progress Report July 1–September 30, 2003

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Project Description

Problem. Work performed by the National Water-Quality Assessment (NAWQA) Program Potomac River Basin study unit (1992-95) indicated that elevated concentrations of nutrients in surface and ground water in the basin often result from human activities such as manure and fertilizer application. A watershed model of the basin is needed to assess the effects of point and nonpoint nutrient and sediment sources on water quality in the Potomac River and its tributaries.

Objectives. The USGS is responsible for the following objectives: 1) compile necessary data for simulation of Potomac watershed processes, using the Hydrologic Simulation Program-FORTRAN (HSPF); 2) create necessary control files for HSPF simulation of the Potomac River Basin, following the framework developed by CBP for Phase 5 of the Chesapeake Bay Watershed Model (CBWM); 3) develop and implement innovative calibration procedures to improve HSPF model calibration; 4) calibrate an HSPF model for the Potomac River Basin; and 5) prepare reports on calibration and analysis of model results.

Benefits and relevance. The calibrated Potomac Watershed Model will allow resource managers to simulate the effects of land-use changes and best management practices on water quality and evaluate alternative approaches for correcting existing water-quality and water-quantity problems within the Potomac River Basin. The proposed study also meets several goals of the USGS Water Resources Division (WRD).

Approach and methods. The proposed study will involve the following tasks: 1) compilation of existing input data, development of model segmentation and network, processing of time-series data, and compilation of ancillary data and observational data for model calibration; 2) development of a model calibration strategy through implementation of existing software for general inversion and calibration of multi-parameter hydrological models; 3) calibration of hydrological and water-quality model (sediment and nutrients); 4) analysis of model results, including consideration of specific study questions; and 5) dissemination of calibrated model and preparation of final reports analyzing the model results.

Progress During Reporting Period

During the past 3 months, the following tasks were completed by the USGS:

1. F-tables were completed for reservoirs.

2. Modeled meteorological fields (precipitation, temperature, PET) were examined for consistency with station data and in regard to applicability to hydrological modeling.

3. Completed initial version of MATLAB-based post-processor for hydrology calibration. Expanded statistical tests that are now available include variance and other measures on log-transformed variables, residuals and percentile and quantile-quantile plots, and tests of normality for both raw and log-transformed data.

4. Analysis of recession for the initial estimates for AGWRC (active ground-water recession parameter) was completed.

5. The hydrological hydrograph separation model PART was modified to be used as a subroutine for processing simulated and observed daily values as part of the post-processor; baseflow and quick flow components were added to the cal5 post-processor.

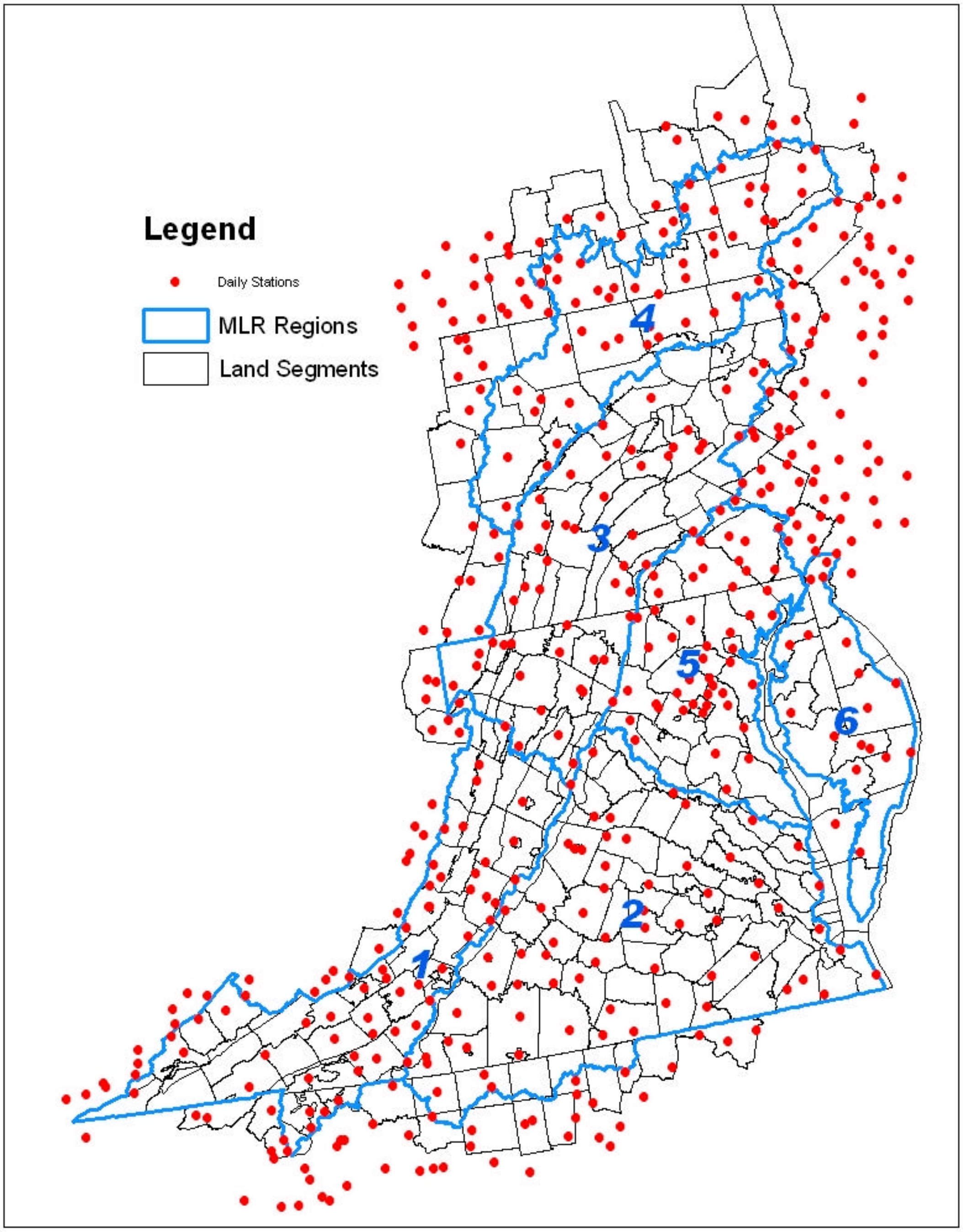


Figure 1. Sub-regions for hydroclimatological analysis and location of daily stations.

F-tables for Reservoirs (Gary Shenk, CBP; Alan Simpson, USGS, Richmond)

Gary Shenk (CBP) has written the code necessary to take F-tables that vary from month to month and put the variation into the river UCIs on a daily basis during the months of change. Alan Simpson (USGS, Richmond) has completed the development of F-tables for reservoirs based on observed or recorded outfalls. Initial tests have demonstrated that the method does a very good job of simulating reservoir outflow. Alan Simpson will present this work at the October 14-15 Modeling Subcommittee Meeting.

Modeling of Precipitation, Temperature, and Potential Evapotranspiration (Lauren Hay, USGS, Denver, Colorado)

The methods used have been described in previous progress reports (see box below). The model developed by Lauren Hay was run with the following options: beginning and end dates, January 1, 1984, and December 341, 1999, respectively; the search distance for hourly disaggregation was set to 1,000 km, and the percent daily volume to match for selection of a disaggregation site was set to 75% (this may be adjusted later); PET was distributed over daylight hours and a Hamon coefficient of 0.0055 was used.

For spatial modeling of precipitation and other hydroclimatological variables, the modeled region was divided into six sub-regions (Figure 1). The regressions were developed for each region on a monthly basis. The adjusted r^2 values for the regressions for precipitation are shown in Figure 2. Comparison of estimated daily mean precipitation at a grid point with the nearest station (Figure 3) indicates a reasonable fit.

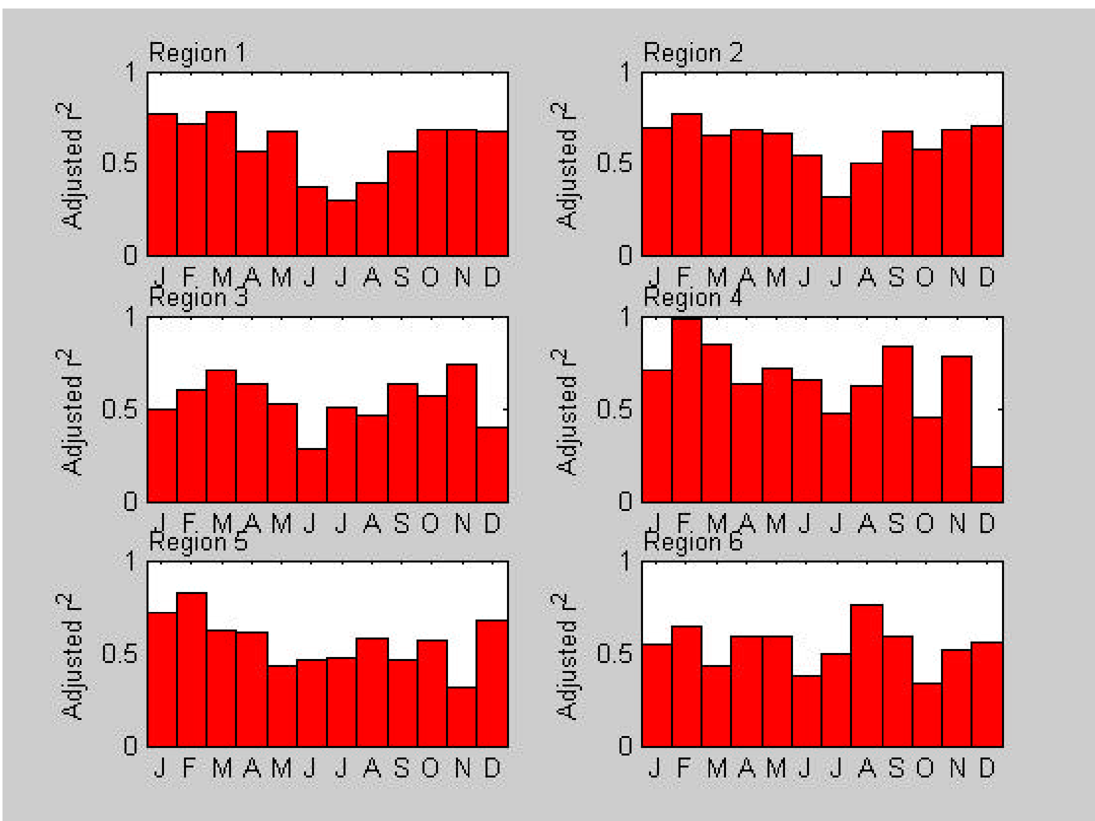


Figure 2. Average adjusted r^2 values for monthly precipitation by sub-region.

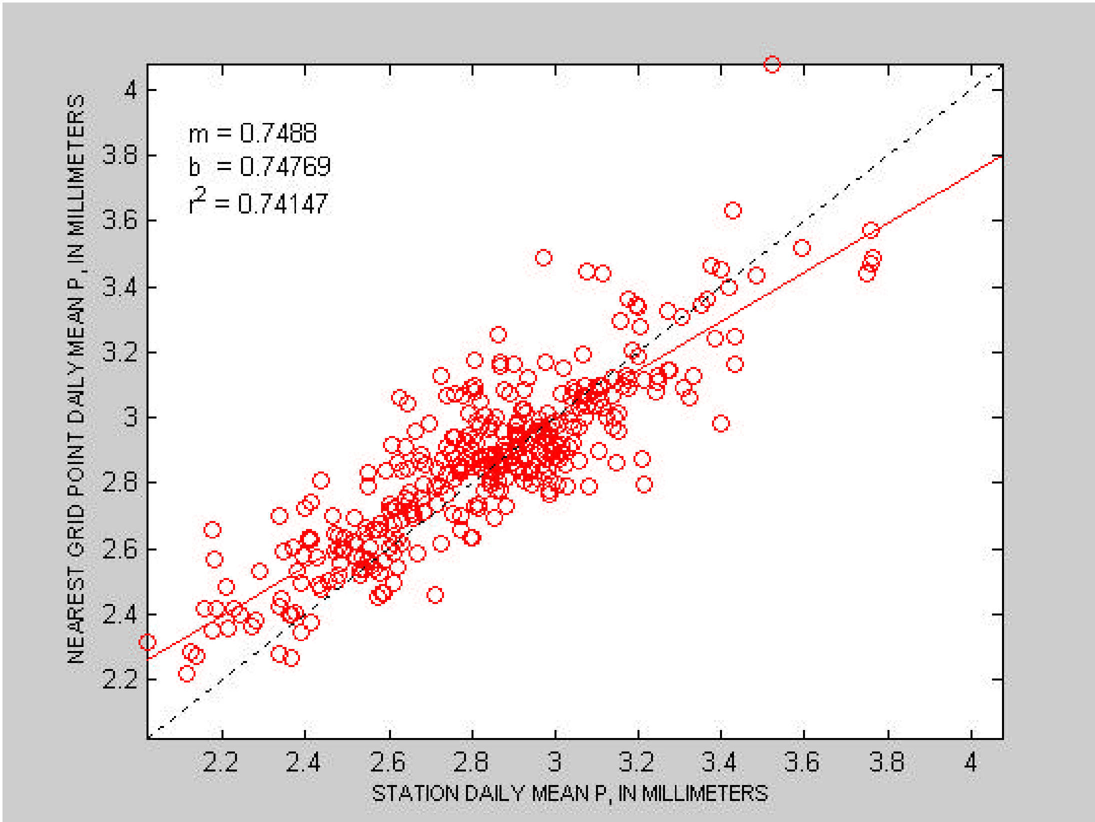
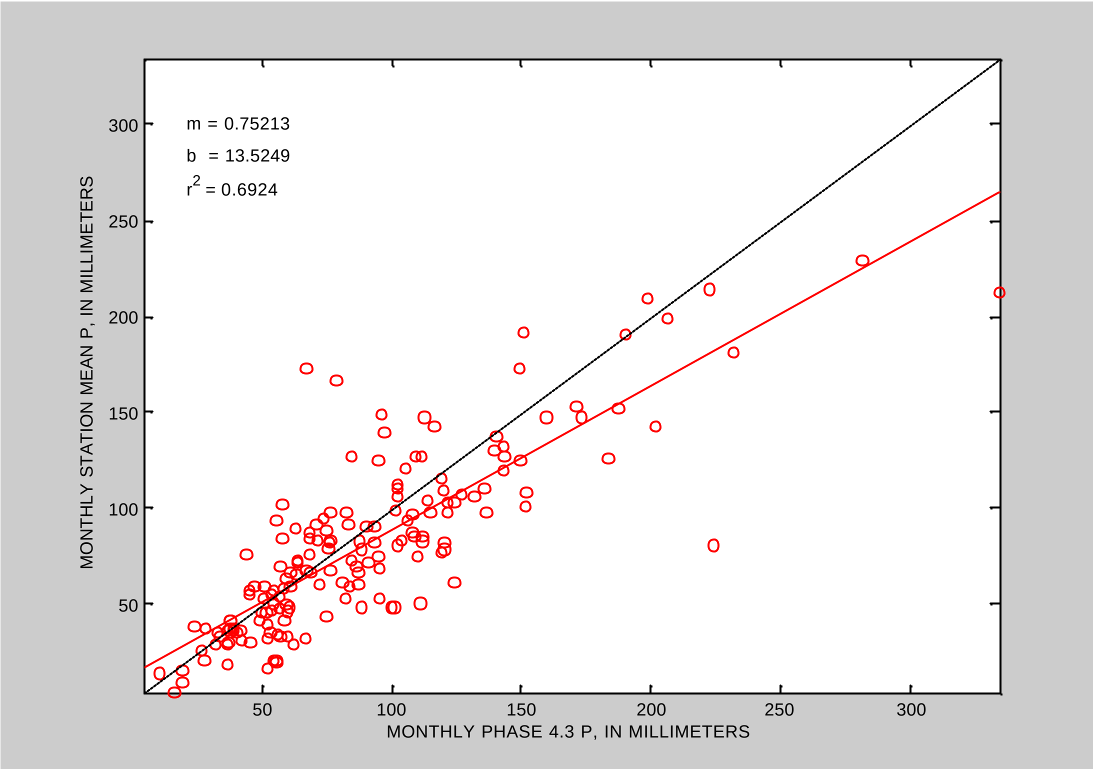


Figure 3. Daily mean precipitation at nearest grid point versus individual station mean daily precipitation for the period modeled (1984 through 1999).

Finally, a number of comparisons were made between station data within a land segment and estimated Phase 5 and Phase 4.3 monthly precipitation estimates within that land segment (Figure 4). Typically, regression analysis indicated an improvement in estimation as reflected in r^2 values that increased from approximately 0.7 to values greater that 0.97.

Daily and hourly precipitation, hourly temperature, and daily and hourly PET time series were converted to WDM files, and monthly and annual summaries prepared.



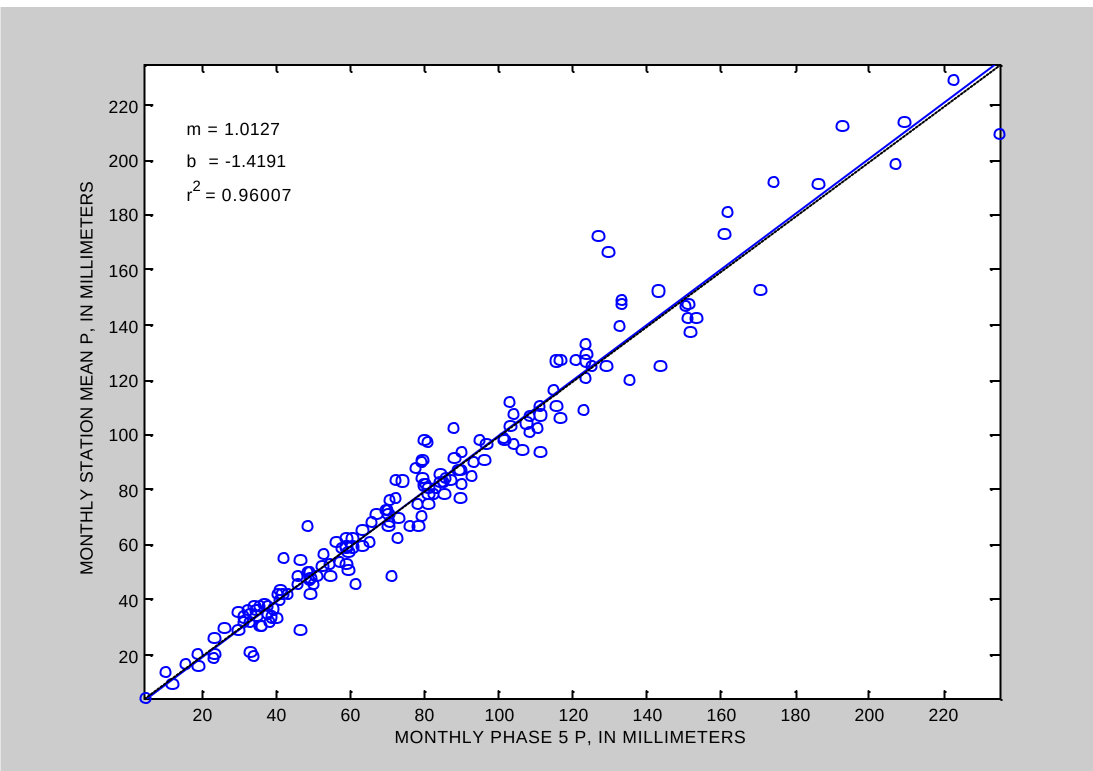


Figure 4. Monthly station precipitation plotted versus Phase 4.3 (top) and Phase 5 (bottom) estimates for a land segment.

Development of a Graphical Post-Processor (Joe Vrabel, USGS, Baltimore)

A graphical post-processor has been developed in MATLAB by Joe Vrabel that provides a number of plots of simulated and observed data and statistical tests that provide insight into the accuracy of the simulation (Figure 5). This tool will see continued development over the project period, through calibration and analysis of the model results. At present, for hydrology calibration, the summary statistics that are incorporated include:

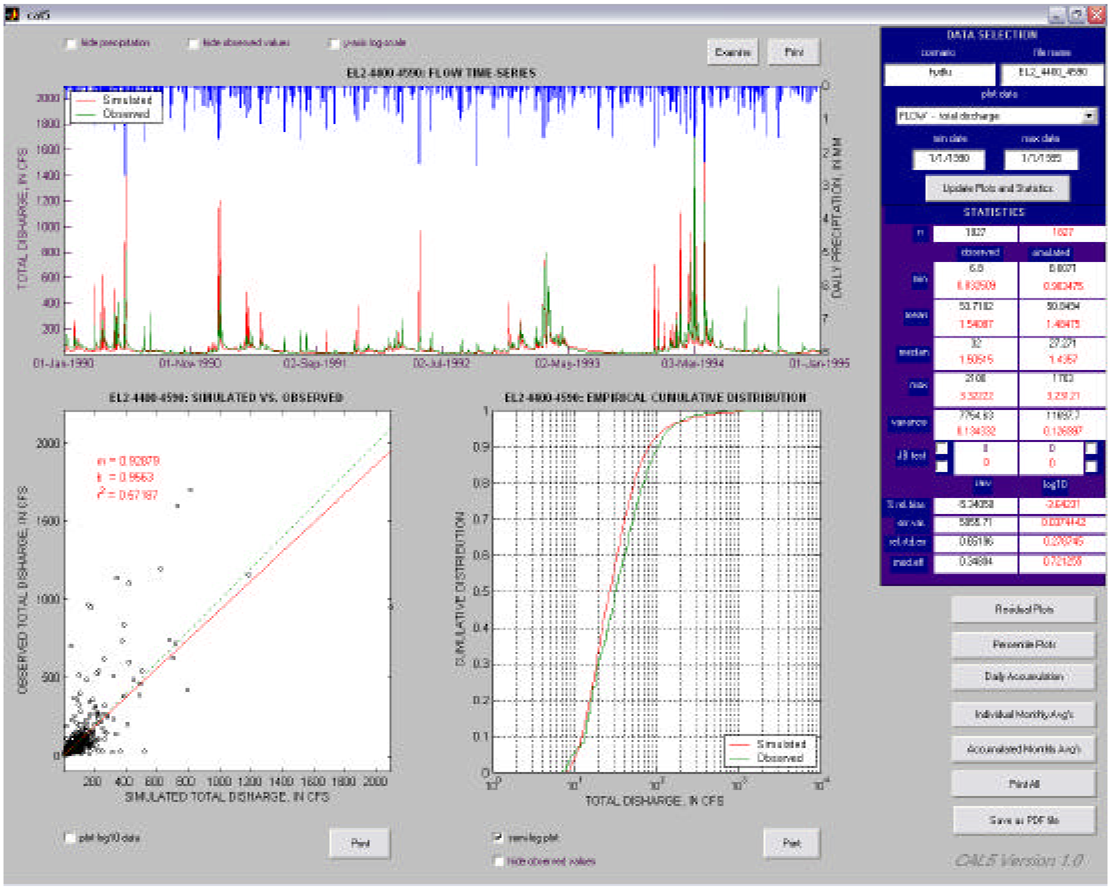


Figure 5 CAL5 post-processor, version 1.0.

1. Observed daily discharge, o: N daily values
2. Simulated daily discharge, s: N daily values
3. Mean, $\overline{o}$, $\overline{s}$:

$$\overline{o} = \frac{1}{N}\sum_{i=1}^{N} o_i \qquad\qquad \overline{s} = \frac{1}{N}\sum_{i=1}^{N} s_i$$

4. Median: the middle value in a series of ranked values.
5. Variance, s_o^2, s_s^2:

$$s_o^2 = \frac{1}{N-1}\sum_{i=1}^{N}(o_i - \overline{o})^2 \qquad\qquad s_s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(s_i - \overline{s})^2$$

6. Error variance, s_e^2:

$$s_e^2 = \frac{1}{N-1}\sum_{i=1}^{N}(s_i - o_i)^2$$

7. Relative bias, r_b:

$$r_b = \frac{1}{\bar{o}}\left[\frac{1}{N}\sum_{i=1}^{N}(s_i - o_i)\right]$$

8. Relative standard error, e_s:

$$e_s = \frac{s_e^2}{s_o^2}$$

9. Nash-Sutcliffe model efficiency, E:

$$E = 1 - e_s$$

The efficiency is like a statistical coefficient of determination (Beven, 2001), or r^2 value. It has a value of one for a perfect fit when s_e^2 = zero; it has the value of zero when $s_e^2 = s_o^2$, which is to say that the model is no better than a one-=parameter "no-knowledge" model that gives a prediction of the mean of the observations for all time steps. Negative values of E indicate that the model is performing worse than the "no-knowledge" model.

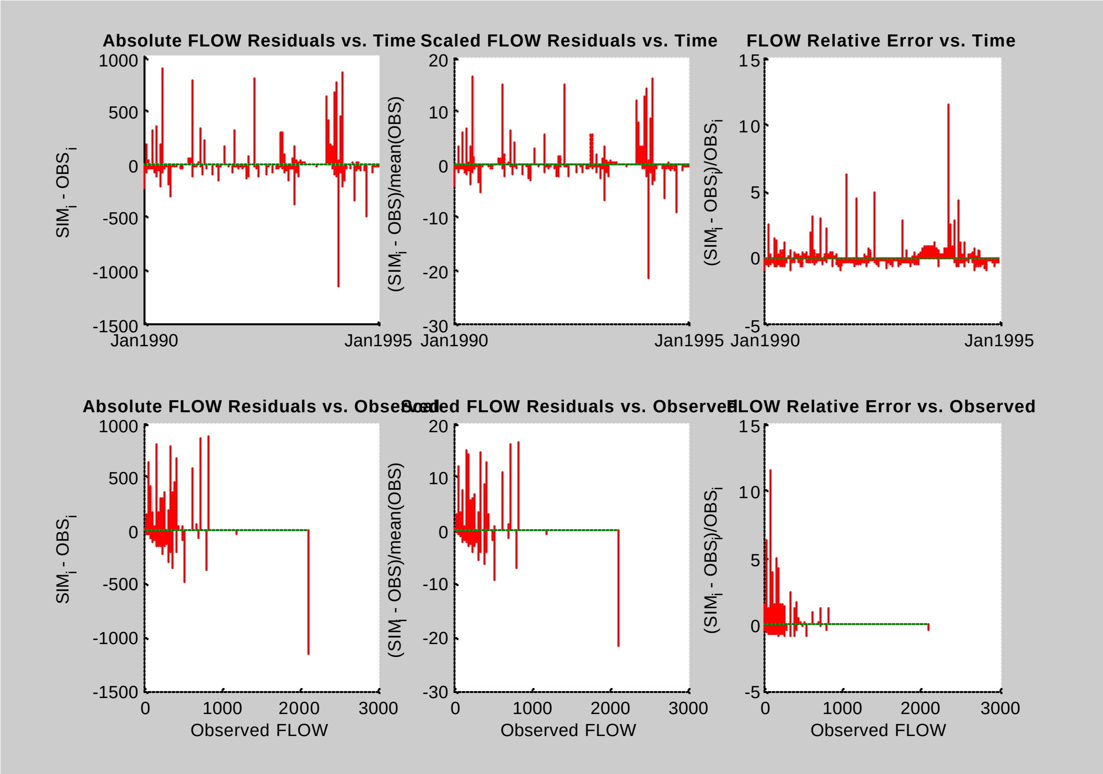


Figure 6. CAL5 residuals plot for discharge.

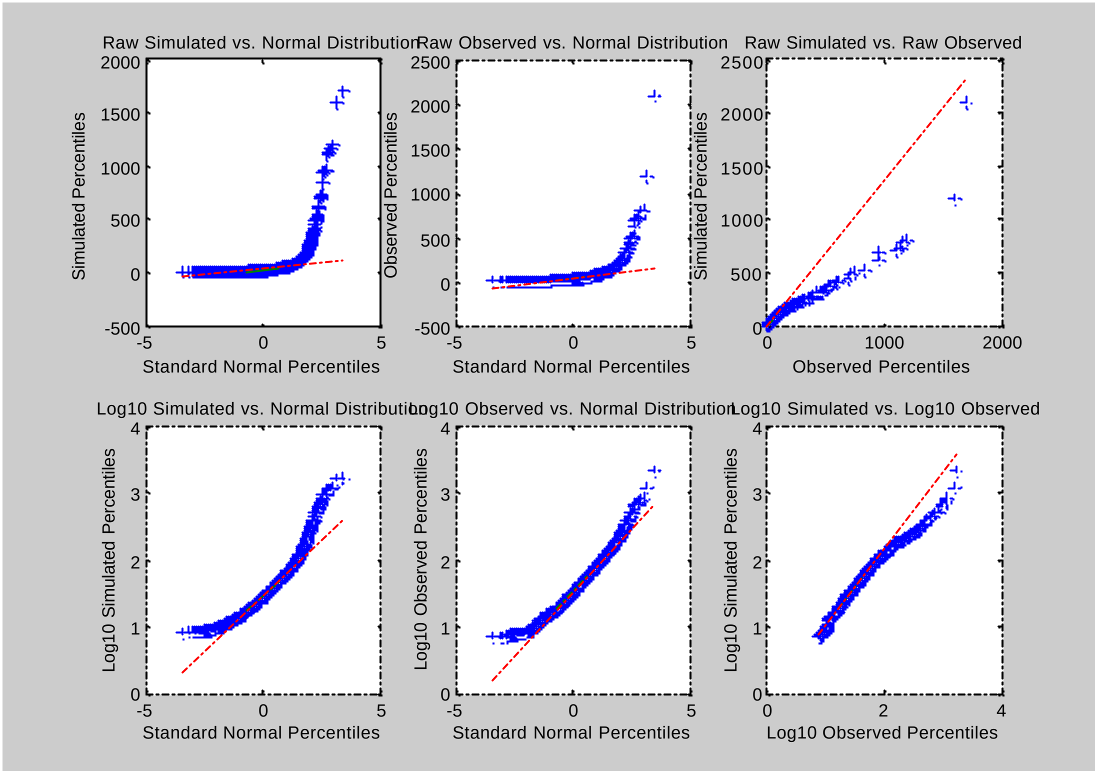


Figure 7. CAL5 percentile plot for discharge.

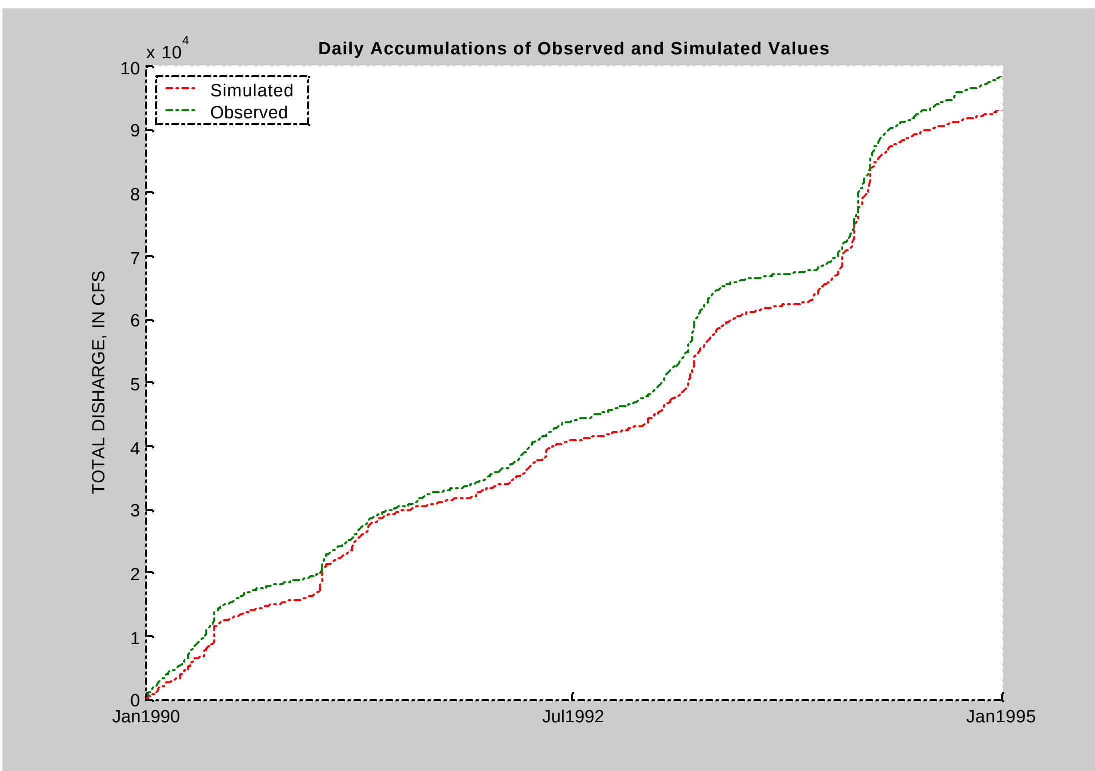


Figure 8. CAL5 accumulated discharge plot.

Additions to the post-processor over the past three months include:

1. Complete statistical tests for log-transformed data.

2. Tests for normality of untransformed and log-transformed data.

3. Residuals plots (Figure 6).

4. Percentile plots for discharge (Figure 7).

5. Accumulated discharge plot (Figure 8).

Recession Analysis for Initial Estimates for AGWRC

The USGS program RECESS (Rutledge, 1998) was used to determine the median recession index for 154 USGS gaged watersheds in the modeled region. Many of these watersheds had previously been analyzed by Rutledge and Mesko (1996) for the RASA project. In general, application of RECESS is limited to watersheds of moderate size that do not experience significant diversions or other human flow modification. Only winter recessions were analyzed, in order to best capture the hydraulic characteristics of the active ground-water zone when evapotranspiration is expected to be minimal.

RECESS is an interactive program for determining the recession index, which is the same as $1/k$ in a common exponential expression for baseflow recession (Hornberger and others, 1998):

$$Q = Q_0 e^{-kt}$$

where:

Q = the discharge (volume or depth/time)

Q_0 = some initial discharge (volume or depth/time)

k = a recession constant (1/time)

It is sometimes more useful to think of $1/k$, or the recession index, which has units of time. It is equal to the time required for discharge to decay by a factor of e, approximately 2.718.

Once a user has specified which months to examine and the minimum number of consecutive days for recession, the RECESS program shows individual daily flows on a log scale (Figure 9) and calculates the fitted recession index. These values are accumulated over all analyzed recession segments and the median value is determined.

In HSPF, The outflow from active ground-water storage is based on a simplified model. It assumes that the discharge of an aquifer is proportional to the product of the cross-sectional area and the energy gradient of the flow (i.e., Darcy's Law). Further, a representative cross-sectional area of flow is assumed to be related to the ground-water storage level at the start of the simulation time interval (we will be using a one hour interval). The energy gradient is estimated as a basic gradient plus a variable gradient that depends on past active ground-water accretion. Thus, the ground-water outflow is estimated by:

AGWO = KGW*(1.0 + KVARY*GWVS)*AGWS

where:

AGWO = active ground-water outflow (in/interval)

KGW = ground-water outflow recession parameter (1/interval)

KVARY = parameter which can make active ground-water storage to outflow relation nonlinear (1/inches)

GWVS = index to ground-water slope (inches)

AGWS = active ground-water storage at the start of the interval (inches)

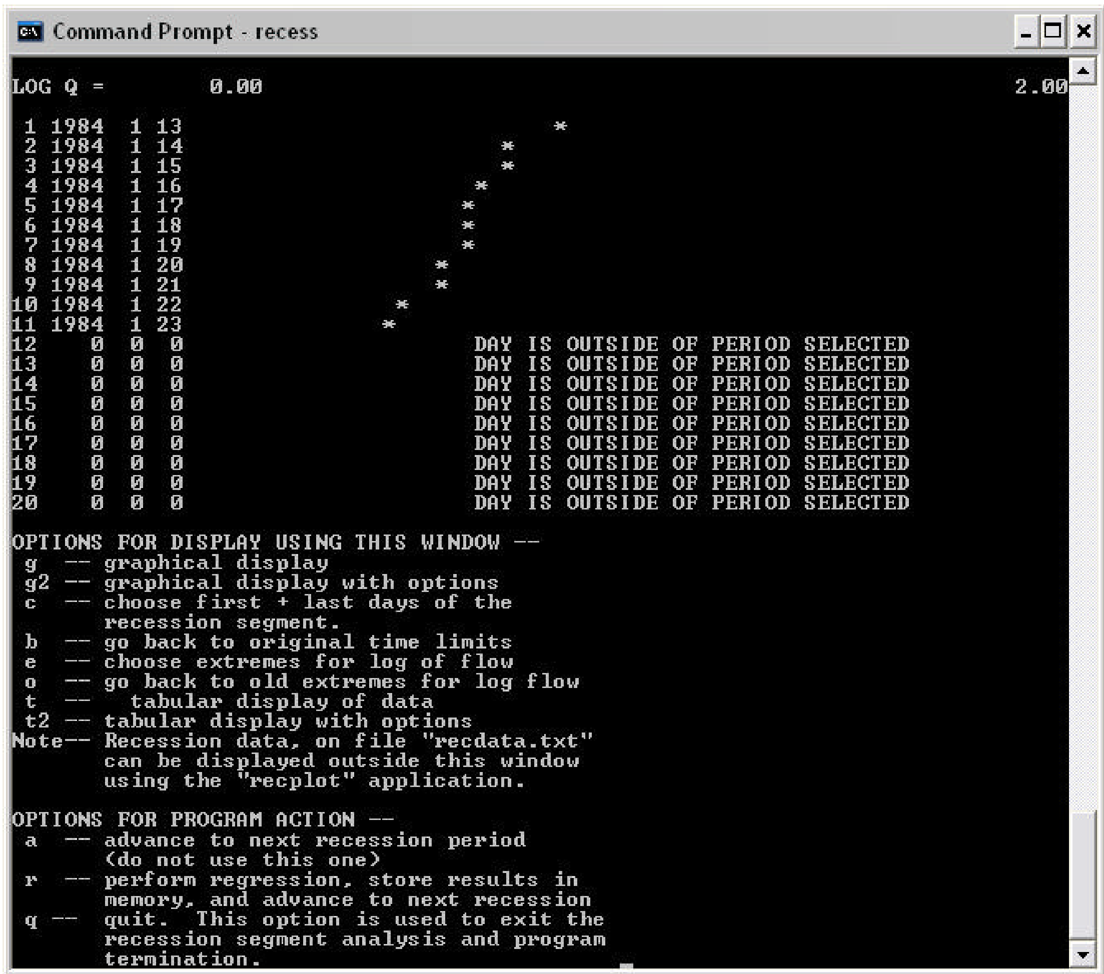


Figure 9. RECESS screen.

For nonlinear recession, KVARY is equal to zero and outflow is simply calculated as:

$$AGWO = KGW*AGWS$$

The parameter KGW is calculated using the relation:

$$KGW = 1.0 - (AGWRC)^{**}(DELT60/24.0)$$

where:

AGWRC = daily recession constant of ground-water flow if KVARY or GWVS = 0.0 (that is, the ratio of current ground-water discharge to ground-water discharge 24-hr earlier)

DELT60 = hr/interval

As long as we are using a one-hour time interval, this becomes:

$$KGW = 1.0 - (AGWRC)^{**}(1/24)$$

For example, if AGWRC = 0.98, then KGW = 0.00084; approximately 0.08 percent of the water in storage is released during the each hour, and the active ground-water storage is decreased by the corresponding amount.

The recession constant k and the HSPF parameter AGWRC are related through these relations:

$$k = -\ln\left(\text{AGWRC}\right)$$

$$\text{AGWRC} = e^{-k}$$

For the example above with AGWRC = 0.98, $k = -0.0202$ days^{-1} or $1/k = 49.5$ days.

The watersheds with calculated recession indices were stratified by HLR (Hydrologic Landscapes Region) and multiple regression was used to develop predictive relations between AGWRC and AQPERMNEW (aquifer permeability); SAND-PERCENT: percentage sand in surficial materials; ELEV-RANGE: range of elevation; ELEV-MEAN: mean elevation; SLOPE-MEAN: mean slope; PFLATTOT-3: percentage of flat area (Figure 10). Once values were determined for every watershed, land segment values were calculated as weighted averages of the watershed values, using intersecting area as weights (Figure 11).

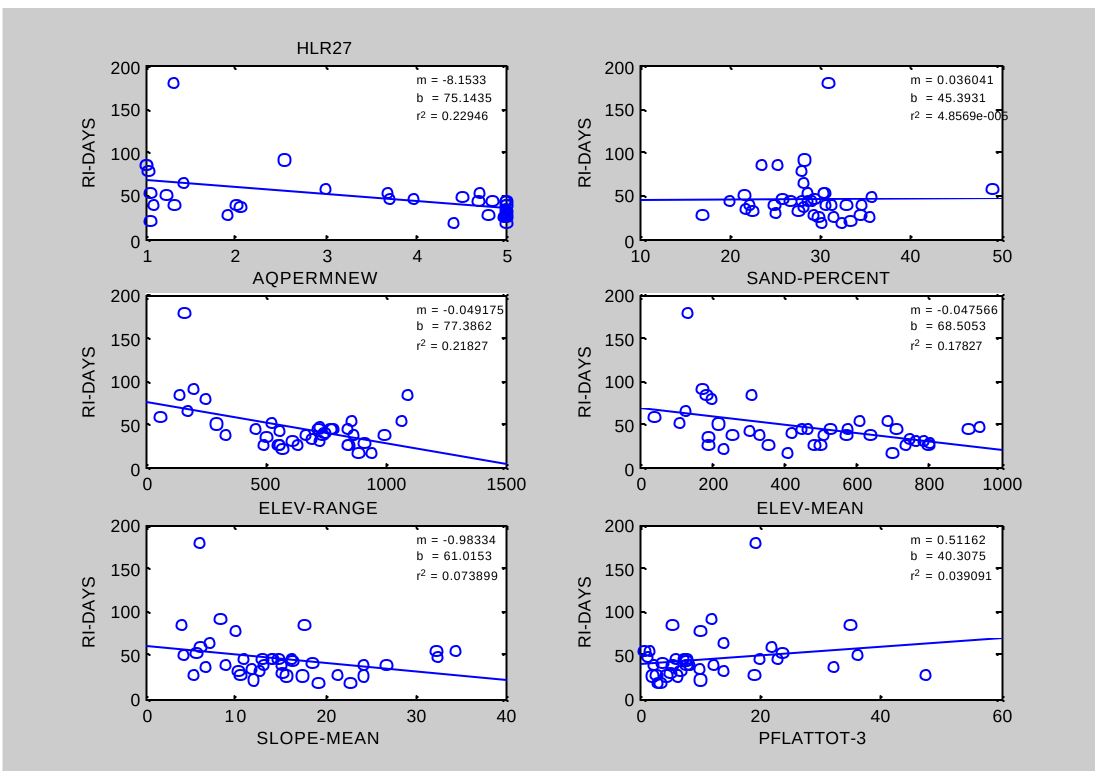


Figure 10 Typical regression results for HLR characteristics versus calculated recession index, HLR number 27.

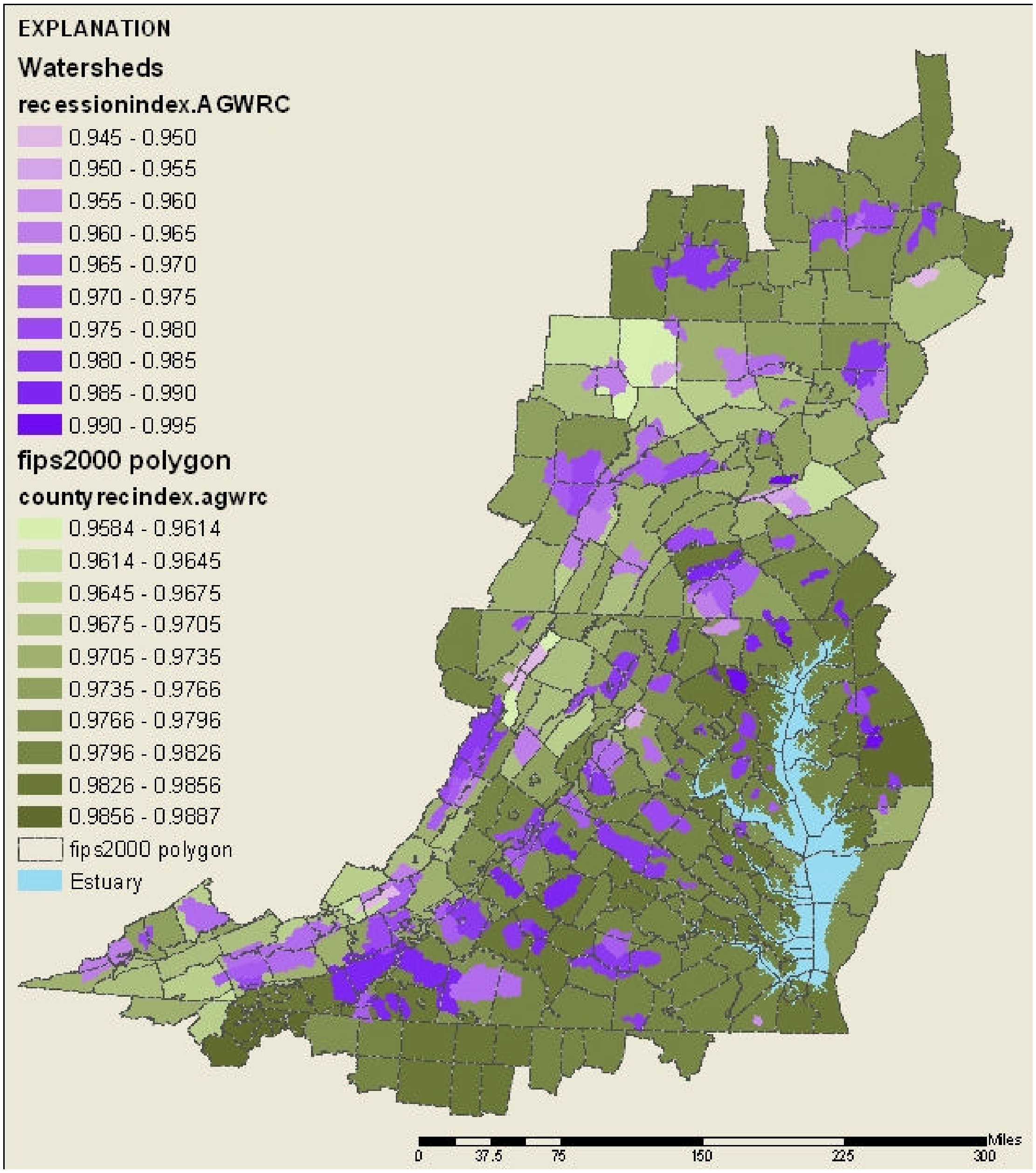


Figure 11. Calculated AGWRC values for selected watersheds and the final values determined for land segments.

Hydrograph Separation Using PART

The USGS program PART (Rutledge and Mesko, 1996; Rutledge, 1997, 1998) separates a daily mean streamflow record into baseflow and quickflow components, based on a simple concept of antecedent streamflow recession. The duration of time after a peak in streamflow during which the components of streamflow due to surface runoff and interflow are significant can be estimated from the empirical relation:

$$N = A^{0.2}$$

Where N is the number of days after a peak and A is the drainage area in square miles. The PART program fills a one-dimensional array of daily mean streamflow data then searches this array for days that fit an antecedent recession requirement. On each of these days, ground-water discharge is designated equal to streamflow as long as it is not followed by a daily decline of more than 0.1 log cycle. It can be inferred that a daily decline more than 0.1 log cycle could indicate interflow or surface flow. The program searches the array again, determining by linear interpolation the ground-water discharge on the remaining days.

The entire procedure is executed three times: once considering the requirement of antecedent recession to be the largest integer that is less than the result of equation 1, and once for each of the next two larger integers. The program constructs a second-order polynomial expression for ground-water discharge as a function of the requirement of antecedent recession, using the three data pairs of ground-water discharge and requirement of recession. Then the program calculates the ground-water discharge for the exact result of the equation above using the polynomial expression.

For our application, PART was re-written as a subroutine that can be called by the post-processor that Gary Shenk developed for the Phase 5 model. Once called, the subroutine calculates the time series of baseflow and quickflow for the simulated and associated observed streamflow for all calibration stations and writes the time series to comma-delimited files that can be read by CAL5 (Figure 12).

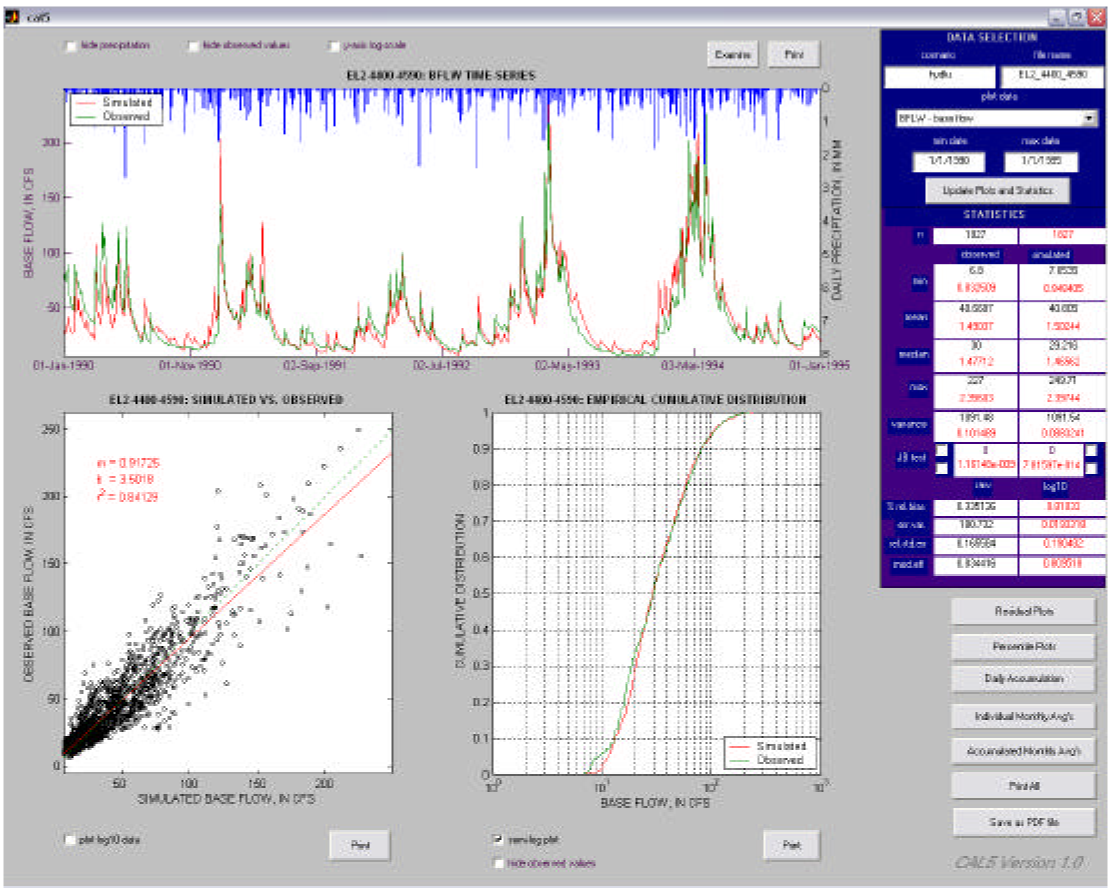


Figure 12. CAL5 window showing simulated and observed baseflow.

Plans for Next Quarter

The next quarter will focus on completing hydrology calibration. The general approach has been described in previous progress reports. Most of the tools have been developed for model calibration (CAL5, post-processors, statistical reporting capabilities, hydrograph separation). Our tasks will involve several individuals manually calibrating individual segments and basins, using these tools and the approaches described previously.

References

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Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.